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A diachronic study of networks of ceramic assemblage similarity in Neolithic western Anatolia, the Aegean and the Balkans (c. 6600-5500 BC)

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Abstract

This study compares the results of Jaccard and Kulczynski-2 similarity measures on a sample of ceramic assemblages to reveal spatio-temporal patterns in the relationship between Neolithic sites in western Anatolia and southeastern Europe (c. 6600-5500 BC). The results show that the relationship between spatial distance and ceramic assemblage similarity increased through time, which supports previous interpretations of leapfrog migrations and subsequent regionalisation in ceramic assemblages during the Neolithic. A diachronic network analysis demonstrates the continuation of Aegean networking after the spread of farming.

Keywords: Anatolia, South-eastern Europe, Neolithic, Network Analysis, Isolation-by-Distance, Ceramics.

INTRODUCTION

The dispersal of the Neolithic way of life from Anatolia to south-eastern Europe has captured the attention of archaeologists for over a century. Similarities between Neolithic archaeological assemblages have been instrumental in shaping views concerning the location and timing of the spread of farming, supporting arguments both for and against the idea that migrations underpinned this process. Today, archaeologists acknowledge that the outline of similarities across the region forms a complex pattern or 'mosaic' of Neolithic cultures in this region (e.g. Tringham 2000, Özdoğan 2011) but it is still debated how such spatial patterns in Neolithic material assemblages evolved. Recent evidence from palaeogenetic research has shown that the first farmers in Central Europe and the Balkans derive from a similar ancestral population as those that settled in north-western Turkey indicating that migration indeed played a major role in the spread of farming to Europe (Mathieson *et al.* 2015, 2017, Hofmanová *et al.* 2016). The first Aegean farmers, in turn, appear to derive from a heterogeneous gene pool that corresponds to several mutually unrelated groups from Anatolia and the Levant (Kılınç *et al.* 2017). It is possible that the Aegean marks a region of extensive interaction and genetic admixture at the dawn of agriculture, and, although conclusive evidence from pre-Neolithic Aegean DNA awaits publication, that resident hunter-gatherers might have contributed to the spread of farming in this region (Kılınç *et al.* 2017, 6-7). In the face of these broader demographic narratives, a diachronic perspective the material assemblage can provide a deeper understanding of the interplay between the chronological asymmetries, technological innovations and social processes that led to the observed regional diversity in Neolithic material assemblages.

With the discovery of new Neolithic sites, and the increasing accuracy of the radiocarbon record, it has become evident that the spread of farming was uneven across the region. The first farmers in the Aegean might have derived from different ancestral populations which took different routes, either by land or sea, from the Neolithic 'core zone', located in northern Syria and south-eastern Turkey, potentially causing the observed variation between 'pioneer' farmer assemblages in the Aegean (e.g. Horejs et al. 2015). Leapfrog migrations appear to have taken place, by which farmers initially occupied desirable areas, such as river and lake floodplains of the Aegean before crossing over to the Balkans (e.g. van Andel and Runnels 1995, 987). The interrupted nature of the spread of farming northwards appears to strongly correlate to the divergence between the environmental and climatic conditions of the Sub-Mediterranean zone (which covers the northern and north-western edge of the Aegean) and the Balkan Peninsula, where such conditions were considerably less favourable, in particular before the end of the 7th millennium BC (e.g. Krauß et al. 2017). Once the first farmers settled in the colder climes of the Balkans, the composition of their faunal assemblages and domestic crops appears to have changed (e.g. Coward et al. 2008, Conolly et al. 2011), suggesting that an important agricultural transition took place somewhere in the Aegean before the expansion of farmers further north. In order to connect the movements and behaviours of the first farmers in western Anatolia, the Aegean, and the Balkans to the observed patterns in the archaeological record, it is therefore important to shift back and forth between different spatial and temporal scales, and while accepting broader demographic trends revealed by aDNA studies, acknowledge that such movements were uneven across the region.

Furthermore, the contribution of interregional networks to patterns in the archaeological record deserves further attention. Complex networks played a role in the distribution of raw materials from the Mesolithic period onwards, as exemplified by the distribution of obsidian from Melos and central Anatolia across the Aegean-facing regions and western Anatolia respectively (Perlès 2001, Milić 2014) and the spatial patterning of chemical signatures in copper-based objects from the Balkans (Radivojević and Grujić 2018). Recent aDNA studies have shown that there was gene-flow between the cattle herds of Anatolia and south-eastern Europe throughout the Neolithic, indicating the continuation of cross-Aegean interactions after the spread of farming (Scheu *et al.* 2015). Such networks must have been important for the transmission of other aspects of the 'Neolithic package' including ground-stone technology, agricultural methods, and pottery technology and style and it is therefore important to study these classes of material culture on similar interregional scales.

The aim of this article is to present the results of a systematic study of the development of spatial patterns in the similarity of ceramic assemblages from Neolithic Anatolia and south-eastern Europe (c. 6600-5500 BC). Although often studied within a narrow regional or local context, ceramics are an important class of material culture with which to study interregional interactions during the Neolithic as they point to wider trends in the connectivity between Neolithic settlements across the regions bordering the Aegean Sea (see also Çilingiroğlu 2016). This research uses spatial statistics to analyse the precise timing and location of these interregional relationships before, during and after the spread of farming to the Balkans, providing a detailed understanding of the development of similarity patterns throughout the Neolithic.

The methods discussed in this article measure the similarity between ceramic assemblages on the basis of shared ceramic attributes relating to decorations, distinctive shape-elements, and surface treatments to identify relationships between Neolithic site-phases. Ceramic attributes might correspond to the tastes, preferences and habits of the users and producers of the pottery assemblages, and, therefore, similarities based on such attributes allude to the transmission of such preferences and tastes between Neolithic settlements as well as the dynamic between agency, history and habitus (*sensu* Bourdieu 1977) that underpin the evolution of cultural traditions on the ground. Ceramic assemblage similarities can therefore be informative about the social and demographic processes that took place during the Neolithic period in the present region. Furthermore, his study will engage in a discussion about the methodologies to reveal similarities between potentially biased datasets by comparing the results of the Jaccard Index and the Kulczynski-2 similarity measure. These measures can help in estimating the influence of variability in the frequency and diversity of attributes in the assemblages and recognise potential biases.

The emergence of a Neolithic mosaic

Since the discovery of the first Neolithic sites in Greece and the Balkans at the beginning of the 20th century, ceramics have played a key role in defining the chronology and outline of Neolithic culture groups (Childe 1925, 1929). Ongoing efforts to define spatial patterns in the archaeological record has led to the identification of, among others, the Anzabegovo-Vršnik group and the Veluška-Porodin group (Gimbutas 1976), the Starčevo-Criş culture (Milojčić 1949) and the Karanovo culture (Mikov 1959). In Turkey archaeologists have identified similarities between the Neolithic assemblages in the eastern Marmara Region, the Izmir Region (Özdoğan *et al.* 2012), and the south-western Anatolian Lakes Region (Duru 2012). This outline of Neolithic culture groups is, however, contentious; different research foci, terminology, pottery typologies, and chronological systems, which also tend to follow modern political borders, have arguably obstructed the comparison of archaeological assemblages across such recent boundaries and the broader area (e.g. Özdoğan 2007). The extent and nature of the observed differences is, therefore, not yet fully understood.

Furthermore, with the discovery and analysis of new archaeological sites, particularly in western Anatolia, new insights into the spread of connectivity between Anatolia and south-eastern Europe can be gained. While recent studies have started to reveal how the ceramic assemblages of these recently discovered settlements compare to known Neolithic ceramic assemblages (e.g. Özdoğan 2015, Çilingiroğlu 2016), comparisons have so far only been descriptive rather than quantitative. Although the complexity of social interactions during the Neolithic cannot be captured through statistical methods alone, they can help to identify patterns in the relationships between site-phases that have generally been studied in isolation. The benefit of using quantitative methods is that, in comparison to qualitative descriptions of similarity, they allow for the analysis of large amounts of data simultaneously, shifting between spatial and temporal scales, creating maps and visualisations, comparing information about ceramics summarised in different typological systems, permitting subsets and the addition of new data incrementally, and allowing for the statistical comparison of information derived from ceramic assemblages to other datasets of archaeological, archaeobotanical, zooarchaeological, genetic or simulated information that use similar spatio-temporal scales.

MATERIALS AND METHODS

Spatial patterns in the archaeological record result from an interplay between the inheritance of cultural information, the adoption of new ideas through social interaction, innovations and chance effects relating to the composition of the population under study (Eerkens and Lipo 2005). Similarities between sites emerge when information is exchanged between peers or peer-groups (horizontal transmission), or when information acquired vertically (from parent to child(ren)) in one location is reproduced in the next. Such modes of transmission are likely to be influenced by spatial distance, given that the cost of movement might affect the transmission of information between distant sites. This is effect is commonly described as 'isolation-by-distance' (IBD) and can be analysed by defining the correlation between cultural similarity and spatial distance (Collard *et al.* 2006, Rogers and Ehrlich 2008, O'Brien and Shennan 2010, Ross *et al.* 2013). Although there is a chance that the ceramic assemblage similarities discussed in this article are spatially organised in this way, it is equally likely that social and geographical factors (such as mountain ranges, large bodies of water or other environmental barriers) influenced the spread of ideas resulting in an irregular spread of ceramic assemblage similarities. Groups that live in close spatial proximity can have very different learning and teaching frameworks, perhaps as a result of the active use of cultural practices and styles to 'signal' social identities or because of a strong conformity of each generation to known traditional practices (Eerkens and Lipo 2005). Furthermore, specific events such as migration, or the individual ways in which communities interact with each other might have affected the transmission of ideas, leading to the emergence of sharp boundaries between neighbouring groups or similarities between distant sites. As such factors potentially create irregularities in the spatial outline of cultural similarities, measuring the correlation between spatial distance and similarity provides a basic way to understand the scale of the influence of such factors on cultural transmission.

This study uses the premise that relatively high degrees of similarity reflect frequently activated social relationships between settlements (e.g. Mills *et al.* 2013, 5785). Although such relationships might correspond to different modes of transmission (horizontally, vertically, or oblique), they should nonetheless be affected by spatial distance in a similar way. The primary aim of this article is therefore to understand how this correlation changes through time. It will also focus on the timing and location of the similarities that underpin the development of spatial patterns in the archaeological record.

From ceramic attributes to similarities

Ceramic attributes were recorded from site-reports, monographs and articles and stored in a relational database, which also included spatial coordinates and chronological information, resulting in a string of attributes relating to spatially and chronologically defined site-phases. In total 87 ceramic attributes relating to a sample of 56 Neolithic site-phases were compared in this study (Fig. 1., supplementary table). The attributes relate to a wide range of different visible characteristics that can be encountered on Neolithic pottery relating to handle, base and rime-types, types of decorations, surface treatments and combinations of surface and paint colours. Such attributes might individually correspond to different teaching-learning frameworks (either endogenous or exogenous) and it is not always straightforward to define which attributes are transmitted in which manner. For example it is likely that rim-types are part of a set of vertically transmitted skills, while more visually attractive decorative attributes might be prone to horizontal transmissions, as might have, for example, contributed to the spread of impressed decorations during periods of intense Aegean networking (e.g. Çilingiroğlu 2010, 2016). However, the dataset may become more vulnerable to biases if a narrow range of attributes is targeted, particularly when using presence-absence information. Some assemblages might have a lower diversity of rare attributes due to sampling biases (e.g. differences in past discard patterns, smaller areas and volumes of excavation, increased influence of taphonomic processes, incomplete excavation or publication, and variation in sampling strategies). Sampling biases might pose a problem for comparing assemblages. Since the chance of discovering rare attributes is generally higher in larger and well-recorded assemblages, this variation would result in higher or lower attribute diversities. In assemblages with high attribute diversity, the chance of a shared match with another assemblage in the dataset is higher and therefore similarities might be skewed in favour of such more diverse assemblages. Because abundance data has not often been made available and it can therefore not be used to compare the effects of sampling biases on pairwise similarities using presence-absence data, this study uses two similarity measures that are equipped to deal with this problem in different ways.

Firstly, this study uses the Jaccard Index to measure the similarity between the assemblages in the sample (Crema et al. 2014; Shennan 1997). The Jaccard Index measures similarity between a pair of samples (site-phases) by dividing the number of attributes present in both assemblages (a), by the total amount of ceramic attributes present only in the first assemblage but not in the second (b), and the number of attributes present only in the second assemblage and not in the first (c). It is expressed as a/(a + b + c). Although it avoids the issue of shared absent values, the Jaccard Index is not equipped to deal with the problem of variation in attribute diversity between assemblages. In general, it overestimates the similarity between assemblages with high attribute diversity while it underestimates the similarity between assemblages with low numbers of attributes (Chao *et al.* 2005).

Kulczynski-2 is a similarity measure that compensates for this problem. It compares pairs of samples by dividing the number of attributes present in both assemblages (a), by the total number of ceramic attributes present only in assemblage one (b) and repeating this for assemblage two (c), and taking the average of both outcomes as the similarity measure. Kulczynski-2 is expressed as (a/(a + b) + a/(a + c))/2. Compared to the Jaccard Index, the Kulczynski-2 has a lower 'richness dependency' than the Jaccard Index, meaning that the variability in the diversity of attributes in the assemblages has less influence on the outcome (Hausdorf and Hennig 2005, 787).

RESULTS

Isolation-by-Distance

Below I discuss the results of my analysis, which tested the correlation between ceramic assemblage similarity (calculated using the Jaccard and Kulczynski-2 measures) and spatial distance. In order to study changes in the relationship between spatial distance and ceramic assemblage similarity, the site-phases were divided into four groups. The first site-phases included in this analysis date to the beginning of ceramic production in the Aegean and western Anatolia (covering the Late Neolithic of western Anatolia and the Early Neolithic in Greece and approximately dating to the period between 6600-6100 BCE); the second group relates to the period in which the first Neolithic sites appeared in the Balkans (corresponding to proto-Starčevo settlements, the later Early Neolithic in Greece, the Late Neolithic - Early Chalcolithic in western Anatolia: 6200-5900 BCE); the third group relates to a time-interval in which the number of sites in the Balkans expands (Starčevo-Criş culture, Karanovo I, and the Greek Middle Neolithic: 6000-5700 BCE), and the last group relates to a period characterised by the abandonment of sites in western Anatolia and the continuation of sites in the Aegean and the Balkans (Karanovo II period and later Middle Neolithic in Greece: 5800-5500 BCE).

Inter-site spatial distance was calculated through the package *fossil* in R (Vavrek 2011), which calculates the Euclidean distance between the site-phases. The correlation between inter-site spatial distance and pairwise similarity calculated through the Jaccard Index and the Kulczynski-2 measure in each interval was compared using a Mantel test (Tab. 1), which is a statistical method that can calculate the goodness-of-fit between two matrices and test it for statistical significance (Mantel 1967). A score of 1 indicates that there is a perfect correlation between the two matrices, while 0 indicates that there is no correlation between the compared matrices.

The results show that there is a general increase in the correlation between ceramic assemblage similarity and distance. In general, this correlation is low in the first interval (6600-6100 BCE), which mainly consists of 'pioneer' assemblages relating to the first introduction of pottery making in the Aegean and the Balkans. It is therefore likely that similar attributes were used across a wide region either because they were introduced by farming groups moving over long distance, or adopted by resident groups as part of a set of skills and ideas relating to pottery technology in general. However, the existence of a pre-ceramic phase in Greece has been debated (Reingruber 2011) and in the light of new radiocarbon dates from settlements in northern Greece (Maniatis 2014, Karamitrou-Mentessidi *et al.* 2015), it appears that the entire area stretching from western Anatolia to mainland Greece was settled by pottery making farming groups by 6600 BC. Furthermore, the first interval covers the period at which the first farmers settled in the Balkans, which might have resulted in the spread of similar attributes across wide distances, contributing to the low correlation between assemblage similarity and geographic distance.

The increasing goodness-of-fit between ceramic assemblage similarity and spatial distance visible in the later time-periods suggests that, once farmers settled down and the populations numbers expanded, pottery attributes were increasingly transmitted between neighbouring groups, and/or that sub-groups settled at closer distance to parent populations. However, as suggested by these figures, the Mantel scores are not particularly high, suggesting that isolation-by-distance is not the only factor influencing intergroup transmissions in the sample. To understand the structure in the dataset in more detail, I will use network analysis to visualise the patterns of similarities through time.

Network analysis

In recent years, methods borrowed from network science have been implemented with increasing frequency in archaeological research (Brughmans 2010, Knappett 2013, Collar *et al.* 2015, Radivojević and Grujić 2018). Such methods can be used to visualise and analyse the location and timing of social interactions and their correspondence to past migrations and exchange and trade networks, improving our understanding of the social processes behind the spatial patterns in the similarity of contemporary Neolithic ceramics. In order to identify relationships between contemporary groups, the site-phases were divided into 200-year time-intervals displayed as network maps with a rolling mean (i.e. 6600-6400 BC, 6500-6300 BC, 6400-6200 BC, etc.). Start and end-dates for each site-phase were derived from a recently published set of radiocarbon dates (Thissen and Reingruber 2016) and, when radiocarbon dates were had large standard errors or were lacking, relative chronological observations made in site-specific publications (see supplementary table). The chronological range was used as a guideline to divide the site-phases in groups; each site-phase was grouped into all of the intervals fitting within its time-range, except in cases where a site had multiple subsequent site-phases in a short time-span. In such cases, site-phases were only grouped into a single time-interval.

The networks were plotted on a geographic map of the area as a way to visualise the spatial and geographical context of the compared site-phases. Networks were produced from the Jaccard and Kulczynski-2 distance matrices calculated for each of the ten time-intervals, using R with the packages *vegan* (Oksanen et al. 2007)*, maptools* (Bivand, Lewin-Koh et al. 2015), and *rgdal* (Bivand, Keitt et al. 2015). The pairwise dissimilarity scores were transformed into networks that show the strength of the relationship between the site-phases through different thickness classes. In order to display only the strongest relationships, the range between the highest and the lowest similarity values in each interval was divided into seven natural breaks. The average of these natural breaks over all the time-intervals was used to create the similarity classes. The network plots only display those relationships that fall within the four highest similarity classes to show the most prominent relationships in the sample (represented by the distinct colours and thickness classes of the edges on the graphs).

Comparing the Jaccard and Kulczynski-2 networks

Both variations of network graphs display strong east-west similarities in the first two intervals (6600-6400 BC; 6500-6300 BC). Within Anatolia, neighbouring sites often have a weak relationship while the first sites in Thessaly, in particular Sesklo, are strongly related to Bademağacı ENI (BM-ENI) and Çatalhöyük Early Tradition and Middle Tradition (CH-ET and CH-MT) in Anatolia. A range of similar attributes that already existed in southern Turkey seem to have reappeared at Sesklo (in particular everted-, incurving- and flattened rim-types, flat-based vessels, vertically pierced knob-handles, flat handles and highly burnished, red-coloured surfaces) suggesting that first sedentary communities in Thessaly reproduced ceramics according to a pre-established idea about pottery making. Within Anatolia similarities are relatively weak during the earliest time-interval, although between 6500-6300 BC Bademağacı ENII (BM-ENII) shares many attributes with Çukuriçi Höyük IX (CuHo-IX). Çukuriçi Höyük IX is a Late Neolithic site-phase that is superseded by a number of earlier occupation phases (the first phase at this site (XIII) has been dated to 6760-6600 BC (Horejs 2016, 146)). The Late Neolithic in western Turkey is generally considered as a period of networking and interaction, unifying previously distinct archaeological assemblages on the Central Anatolian Aegean coast. Çukuriçi Höyük is considered to play a vital role in this process, functioning as a 'gateway' for the transmission of ideas to the sites in this region (Horejs 2016, 151). The outward looking role of Çukuriçi Höyük during this period might be reflected in the strong interregional relationship with Bademağacı.

Given that the network patterns retrieved through the Kulczynski-2 method overlap with that based on the Jaccard Index, we can be confident that these patterns are not biased by differential diversity between the assemblages. A clearer difference appears in the interval between 6400-6200 BC, in which the Kulczynski-2 network shows a stronger relationship between Uğurlu V (UG-V), Hoca Çeşme IV (HC-IV) and sites in Anatolia, which is likely the affect of the low attribute diversity of these sites. This fits with views promoting the potential links between these sites and south-western Anatolia (Özdoğan 1998, Erdoğu 2013).

During the interval between 6300-6100 BC, strong relationships appear between Ulucak Va (UL-Va) and Knossos EN and (in the following interval) Franchthi 1 (FCP-1), while relationships between western Anatolia and Thessaly continue. Such relationships suggest that the Aegean Sea continued to serve as a bridge rather than a barrier for social interactions and inter-group cultural transmission after the spread of farming to Greece. A widely acknowledged marker of such networks is the distribution of obsidian from Melos, which was procured and distributed among sites in the Aegean from the end of the Mesolithic onward (Perlès 2001, Milić 2014). Small groups might have travelled along the Aegean coast and between islands to ship goods and material such as obsidian. Such coastal movements, combined with low-density long-distance movements, could have facilitated the rapid spread of techniques and decorative styles relating to pottery (Çilingiroğlu 2010, 2016). Throughout these early intervals, the sites in NW Anatolia that surround the Sea of Marmara, appear to have played a minor role in such networks, an observation that fits with the diversity within the material assemblages surrounding the Sea of Marmara, and particularly the division between the sites located in the eastern and western halves of this region (Özdoğan 2014). Isolated elements from outside of this region might have infiltrated the assemblage of Menteşe as suggested by its strong relationship with Franchthi and Knossos during the interval between 6200-6000 BC. Only from 5900 BC onwards, stronger relationships appear between Ilıpınar and sites in Turkish Thrace, which might relate to a higher intensity of interaction between the southern Balkans and north-western Anatolia.

Between 6200-6000 BC there appear to have been strong relationships among sites on the Greek mainland. Previous studies have pointed out that we are dealing with 'overlapping' similarities in the archaeological assemblages of Neolithic sites in Greece (Halstead 1984), while the pottery assemblages of the Peloponnese and Thessaly are stylistically variable (Perlès and Vitelli 1994). In the general scale in which ceramic assemblages are compared in the present study, the Greek sites appear relatively similar (these assemblages contain attribute categories such as cream and red-slipped ware red and/or white painted decorations, ring-bases and vessels with stand-feet and bowls with globular, incurving shapes), while the more detailed variation described by Perlès and Vitelli (1994), which may relate to specific patterns of painted decorations or combinations of attributes on a single vessel, is not identified through this method. Such more detailed variation has been informative about defining social dynamics on a narrower local and regional scale, and, while such social processes cannot be captured by the more general approach of this article, it is telling that both areas are strongly related to western Anatolia. It might be, for example, that conformity to using Anatolian attributes was relatively strong in Greece, but that group made their own, individual choices as to how to use these attributes.

The first evidence of Neolithic settlement in northern Greece significantly pre-dates the establishment of Nea Nikomedeia ENI (NEA-I), the earliest northern Greek sites in the analysis, (i.e. Paliambela Kolindros, Phyllotsairi Mavropigi, Revenia and Axos A) (Urem-Kotsou *et al.* 2014), suggesting that NEA-I may represent a later stage in the development of regional pottery cultures in Greek Macedonia. This site is highly similar to Blagotin (BLA-SC), which in turn shares a relatively high number of attributes with Džuljunica I (DS-I), which coincides with the first phase of settlement in northern Bulgaria, suggesting that some stylistic features common in the first Balkan assemblages might have emerged in northern Greece. This result further supports the idea that the Struma river valley must have been an important thoroughfare for early farmers during the initial expansion northwards, which also emerges from recent chronological observations and the distribution of other classes of material culture (e.g. Urem-Kotsou *et al.* 2014, Krauß *et al.* 2017, 7).

In the interval between 6100-5900 BC both networks indicate a strong relationship between Ulucak-4 (UL-IVearly) and Džuljunica-II (DS-II). Similarities between Džuljunica-Smărdeš and Anatolia have been observed in previous studies (e.g. Elenski 2004, Krauß *et al.* 2014) but the similarity networks in my study show that cross-regional transmissions, in particular between northern Bulgaria and the Izmir Region, may have intensified after the initial spread of farming to the Balkans. Recent evidence from aDNA studies conducted on cattle bones has pointed out that geneflow between cattle from Anatolia and the eastern Balkans continued throughout the Neolithic period (Scheu *et al.* 2015). This evidence suggests that farming groups on both sides of the Aegean engaged in networking, which might have intensified after the first farmers settled in the Balkans. Pottery styles and techniques appear to reflect such networks reinforcing the idea that social interactions through networking rather than migration facilitated the development of ceramic assemblage similarities after the initial stages of the Neolithic in this region.

After 6000 BC, we find the complex network patterns continue, crossing the Aegean and the eastern Balkan region. Strong relationships appear in Thrace, a region that covers southern Bulgaria, the European part of Turkey, and north-eastern Greece, and surrounding regions connecting Karanovo in Bulgarian to Džuljunica-II, Magura and finally Ovčarovo-Gorata. Within the Balkans archaeologists have traditionally distinguished between sites located to the north and south of the Balkan mountain range, which have ceramics that are, respectively, vegetal and mineral tempered (e.g. Stefanova 1996). From the current analysis it appears that many attributes were shared among these sites. In fact, the strongest evidence for regionalisation in this sample takes a form very different from the pre-established outline of archaeological ‘cultures’. The similarities observed through the network analysis in particular show that the relationships in Thrace cross the boundaries of the Karanovo culture, Starčevo-Criş culture, the Yantra River valley group, and Turkish Thrace. While these regions are often considered in isolation from each other, this study suggests that in fact their ceramic material is relatively similar.

DISCUSSION AND CONCLUSIONS

The results of this study have captured patterns relating to highly interconnected communities during the Neolithic. These patterns appear to correspond to the spread of farming through leapfrog migrations resulting in widespread similarities in ceramic attributes across the region during the spread of farming in the Aegean (c. 6600-6300 BC) and the Balkans (c. 6200-6000 BC). The observed dissimilarities between some of the neighbouring sites suggests that cultural transmission was organised in a complex manner; the initial farmers in the Aegean might have derived from differing ancestral populations, producing pottery according to their own individual traditions, resulting in diversity between neighbouring sites. Another possibility is that after initial settlement, the combination of attributes reproduced varied between sites, and that local innovations/mutations occurred. This possibility, described as founder effects (e.g. Shennan 2000), explains how diversity appears between the cultural assemblages of sub-groups from a common population.

The patterns relating to the first expansion of farming to the Balkans (c. 6200-6000 BC) indicate that these groups shared pottery styles and shapes with northern Greece. This observation is consistent with van Andel and Runnels' (1995) view of leapfrog colonisation in Greece and recent palaeoclimatological and palaeoenvironmental studies (Krauß *et al.* 2017), which suggests that the Sub-Mediterranean zones of northern Greece might have provided initial environments in which farming packages could have been adapted to the colder conditions of the Balkans before migrations further north were undertaken. The strong similarities between the first ceramic assemblages in the Balkans suggest that such migrations must have been rapid, leaving little room for innovations/mutations to appear in these potting traditions. Farming might have arrived to Thrace somewhat after the initial dispersal of farming to the Balkan vegetation zones, which might be due to its extreme microclimate and magnified effect of Rapid Climate Change events during the Early Neolithic, posing a more challenging environment to settle initially (e.g. Krauß *et al.* 2017). The strong similarities that emerge between the ceramic assemblages in Thrace indicate that shared practices evolved in this region while sites in Anatolia were largely abandoned after 5700 BC. All throughout these periods of migration, the Aegean facing regions seem to have continued to interact, sharing ideas and innovations relating to pottery production and style in the process. The continuation of these networks, which were already facilitating the spread of obsidian from Melos since the Mesolithic period, indicates that the Aegean played an important role shaping social interactions across the region during the Neolithic.

The Jaccard dissimilarity Index and the Kulczynski-2 similarity measure provide largely similar results. Differences in the Jaccard and Kulczynski-2 networks are only notable in some of the individual pairwise relationships, but such difference do not change the general outline of relationships much, suggesting that the different degrees of diversity between small and larger assemblages have little effect. These methods therefore seem capable of picking up meaningful patterns, corresponding to known theories about the spread of farming, and social interactions during the Neolithic in the regions discussed. This is contrary to the idea that ceramics represent regional or domestic processes alone, and it rather appears that ceramics reflect the intensity of movements and social interactions of Neolithic farmers in this region. Future comparative studies using other strands of archaeological data or a new dataset with quantitative information derived from ceramic assemblages or the inclusion of additional attribute classes in the existing dataset might further improve our understanding of these pairwise relationships. Nevertheless, it is evident from the present study that ceramic assemblage similarities can contribute to countering ideas about Neolithic settlements as stationary, self-sufficient units, as they exemplify the complexity of social and demographic processes that underpin the spread of ideas and practices during this period.

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Table 1. Mantel r^2 values of the correlation of Jaccard dissimilarity and Kulczynski-2 similarity with spatial distance.

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